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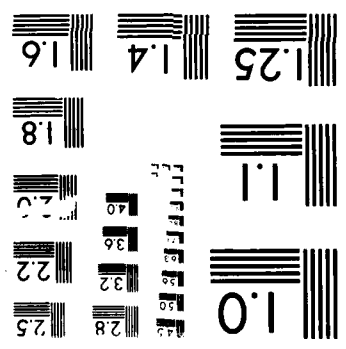
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AURORAL AND SUB-AURORAL INTERACTION
AT THE F REGION IONOSPHERE

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<p>→ Deterioration of satellite signals and fading on HF are results of the appearance of intense irregularities of the order of meters to several hundred meters in the F layer. At auroral and sub-auroral latitudes the irregularities become intense and create serious problems. The interaction of the ionosphere during magnetic storms has been studied at auroral and sub-auroral latitudes. Results include a model which shows the expansion of storm effects during the injection phase of the magnetic storm and the effect of the stored up energy in the ring current during the recovery phase. In comparing observations with incoherent scatter data from Millstone Hill the total convection velocity appears to be the dominating parameter in the injection phase creation of irregularities. The work will move to studying the global effects of individual storms since the storms can inhibit irregularities at the equator while creating them at auroral and sub-auroral latitudes.</p>					
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I. RESEARCH OBJECTIVES

A. INTRODUCTION

Small scale irregularities of several hundreds of meters to meter size located in the F layer from 200-600 km in altitude are of interest from the physics point of view and are important in producing effects on radio transmissions. Physicists want to understand the instability mechanisms responsible for their growth, as well as the stability and decay of the irregularities. Technology is mostly interested in the modelling of the irregularities so that they can be forecast and the effects minimized.

The areas affected by these irregularities which vary from meter to kilometer size are shown by the view of the nighttime occurrence of F-layer irregularities in years of high sunspot numbers (1989-1991) (Figure 1). The two worst cases in this illustration of global patterns occur in the equatorial anomaly region (15-20 degrees from the magnetic equator) and the polar region. In the polar region a flight in 1989 showed fully saturated (20 dB fading) for 23 of 24 hours at 250 MHz.

From the system point of view important deterioration can be observed in HF transmissions and in satellite communications and navigation. In the equatorial region fading is observed on all systems below 4 GHz. The results will assist in minimizing the effect of these F layer irregularities thru the use of modulation techniques which take into account the fading characteristics of the medium. The extent of the fading in both geographic and geomagnetic coordinates and its morphology as a function of various parameters will assist in warning systems users when there will be problems with the medium.

The nature of the irregularities their origin, development and decay are being studied with the objective to increase the understanding of their physics and morphology. With the understanding of the physical processes and characteristics of the irregularities, the fading due to the irregularities could be forecast and minimized. For this study we have emphasized the coupling and decoupling of auroral and sub-auroral F-layer irregularities.

II. THE RESEARCH PROGRAM

In order to understand the dynamics of the production of ionospheric irregularities in the sub-auroral and auroral latitudes, a coordinated program of optical, incoherent scatter radar and radio observations was proposed. The geomagnetic region encompassed Corrected Geomagnetic Latitudes ranging from 30° to 65° . The study utilized the all-sky airglow and auroral monitoring systems of the Boston University Mobile Ionospheric Observatory, the Millstone Hill Incoherent Scatter Radar in Westford, Mass., and a chain of satellite receiving stations in Goose Bay Labrador and in the vicinity of Boston, Mass., as well as other participating foreign observatories in a program designed to study this geomagnetic sector. In addition in-situ measurements of precipitating particles were examined.

The ionospheric intersections available through the use of cooperative programs included the following:

TABLE 1
LOCATION OF STATIONS

	Geographic Latitude	Geographic Longitude	CGL
Goose Bay, Labrador (Beacon Satellite)	59°N	66°W	$70-71^\circ$
Halley Bay, Antarctica (Ionosonde)	76°S	27°W	61°
Sagamore Hill (Beacon Satellite)	50°N	77°W	61°
Goose Bay, Labrador (GOES 2)	48°N	73°W	60°
South Uist, UK (Ionosonde)	57°N	7°W	58°
Sagamore Hill, MA, USA (GOS 2)	39°N	77°W	53°
Slough, UK (Ionosonde)	52°N	0°W	51°
Argentine Islands, Antarctica (Ionosonde)	65°S	64°	49°

A series of pilot studies had indicated the existence of stable auroral red arcs (SAR Arcs), auroral emission, and scintillations in the region probed by the coordinated series of experiments. The ultimate goal was to obtain a working model of irregularity formation and decay in the auroral and sub-auroral regions. The question was what were the necessary conditions for the generation and maintenance of irregularities in the F region of the ionosphere at auroral and sub-auroral latitudes. Various instability mechanisms as well as precipitation have been proposed for the generation of the irregularities. To understand the physics it was necessary to study simultaneously the sub-auroral and auroral regions.

III. THE RESEARCH STUDIES

A. THE RING CURRENT AND SUB-AURORAL F-LAYER IRREGULARITIES

From earlier studies it was clear that auroral F-layer irregularity intensity occurrence was a function of solar flux and magnetic activity. Sub-auroral F-Layer irregularity occurrence could be understood by ordering the data in step with the time development of the ring current during a magnetic storm. During magnetic storms two areas of irregularities exist,

one relating to the plasmapause and the second to the auroral oval, straddling the minimum electron density region of the trough.

For the sub auroral region, when data are statistically examined, there is little evidence for the correlation of irregularity intensity and occurrence as a function of Kp except for very high K indices. In analysis of specific periods involving magnetic storms at sub-auroral latitudes (March 4-6, 1981 and October 20-25, 1981) as outlined in Aarons, Gurgiolo, and Rodger, 1988 (Radio Science), it was noted that high sub-auroral irregularity intensities were observed during both the growth phase and the recovery period of the magnetic storms; in the recovery phase there was little magnetic activity as shown by Kp values or local magnetograms. It is clear that during initial phases of strong magnetic activity, the region of F-layer irregularities extends to what were "sub-auroral latitudes".

F-layer irregularities are detected by a variety of techniques including spread F from ionosondes, scintillation of radio transmissions from transmitters, and in-situ observations by rockets and satellites. Scintillation and ionosonde data from several stations ranging from 50°-71° corrected geomagnetic latitude in both hemispheres were used to show that the energy from magnetic storms stored most probably in the ring current is a primary source of energy for the formation of F-layer irregularities at sub-auroral latitudes in the region of the plasmapause during the recovery phase of a geomagnetic storm.

The accepted measure of the ring current other than that made by in-situ probes, is that of the Dst index. It is the hourly magnitude of the normalized horizontal component of the Earth's magnetic field, as *determined from data obtained from several low latitude geomagnetic observatories well distributed in longitude*. The Dst index does not include localized effects; it smooths out some small-scale temporal changes. The ring current plasma contains several ions species at many energy levels. We used Dst because of its availability; it is not believed that all of the ions at all energies are effective in producing sub-auroral irregularities either directly or creating the necessary conditions for irregularity development but the index is readily available over many years and can be used in conjunction with observations made over long periods.

Using case studies and statistical analyses of the relationship between Dst and F-layer irregularity occurrence and intensity, we showed (Aarons and Rodger, 1989) that the ring current is an important source for the energy needed to create conditions for the development of sub-auroral F-layer irregularities. This has been achieved by close examination of two study periods concentrating especially upon the recovery phase of the storm when geomagnetic activity as indicated by the Kp (or local K magnetic) index has subsided. The concentration of the statistical portion of the research was on the similarity in the behavior of sub-auroral irregularity intensity during the recovery stages of magnetic storms and Dst. We found for example that the correlation coefficient for Dst against nighttime irregularity index was the following:

Date	Correlation Coefficient
May 1981	0.64
September 1984	0.52
November 1986	0.71

Similar statistical analyses has been carried out for 12 different months in the period 1981-1986. Integrated scintillation index for the night was correlated both with the mean Dst and the mean Kp index for the time period 2100-0900 UT. In all cases except the one discussed below, a statistically significant relationship was obtained for Dst correlation and this was consistently appreciably higher than those for the Kp study. For these same months we have computed correlation coefficients for integrated scintillation intensity with the change in Dst between 2200 and 0900 LT for each night: we found consistent lower correlation coefficients (0.04, 0.14, and 0.38).

Although the relationship between the occurrence of sub-auroral irregularities and Dst is statistically highly significant for periods when there is magnetic activity, we have to address the question why it is not perfect. There could be two fundamental reasons for this. First, as already indicated, the index Dst may be a good but not ideal descriptor of the time variation of the energy transfer from the ring current to the ionosphere at sub-auroral latitudes. Secondly if Dst is low for a particular month for example, other mechanisms for producing irregularities may be operative. In the one case cited above F-layer scintillation was of low level and Dst stayed near the zero level. Other mechanisms were operative for producing low intensity irregularities.

The plasma instability acting at these sub-auroral latitudes has not been uniquely identified. We propose that the ring current is the major energy source of plasma irregularities in the F layer at sub-auroral latitudes during the recovery period of a magnetic storm.

B. THE SEPTEMBER 1984 STUDY PERIOD AND MILLSTONE HILL OBSERVATIONS

1. Introduction

The period of September 17-24, 1984, the Equinox Transition Study period, has a plethora of geophysical conditions including very quiet periods as well as magnetic storms. The Millstone Hill Ionospheric Radar was on the air with meridian scans for 24 hours for each day. The Millstone parameters obtained through the use of the Boston University data processing color graphics allowed the plotting of electron temperature, electron density, and ion velocity from 25°N to 60° geographic latitudes thus encompassing the plasmopause and the auroral regions. The satellite beacon observations (6 sources) have trans-ionospheric intersections from 39° geographic to 60° geographic. The data has been reduced. Joint studies with the staff of Millstone have been started. The concept is to see what were the necessary conditions for the development or convection of irregularities. Several hypotheses were examined for correlation of ionospheric parameters and scintillation.

2. Convection and scintillations at mid-latitudes during storm onset

The first paper on this study from the data set was developed by Foster and Aarons (1988) using the convection pattern of Millstone Hill observations. A small magnetic storm occurred on Sep 19, 1984 with Dst, the ring current energy measurement, decreasing abruptly to -67γ near 1200 UT (07 LT). Normally the ring current sets up a shielding layer. However the shielding layer takes time to grow. We were able to show that the magnetospheric shielding layer was coincident with the observed reversal between sunward and antisunward convection.

Storm enhanced neutral winds at latitudes equatorward of the shield layer generate a long lived perturbation electric field in the inner magnetosphere. The sub auroral electric field grows as the shielding boundary moves poleward. We observed relatively large 136 MHz scintillations in both the auroral sunward convection region and the region of sub-auroral antisunward convection when the convection electric fields exceeded 5mV/m .

During a sudden change in ring current energy on Sep 19, the convection pattern and the scintillations could be correlated. The pattern observed could be isolated since night scintillations had ceased and since the convection pattern had returned to its normal morning levels. The presence of high plasma velocities was shown to be correlated with the occurrence of scintillation activity. When high velocities and a high gradient of velocity were noted on the incoherent scatter radar, scintillations were observed. When lower velocities were recorded that morning, scintillations ceased. Two latitudes in one longitude region were probed, 61° CGL and 53° CGL.

This correlation appears to hold for various periods in the Sep 17-24 time frame. Intense F-layer irregularities are observed when there is high plasma convection in the auroral region during magnetic storms. In draft form is a paper by J. Aarons, J.C. Foster, and A.S. Rodger on this subject using the Sep 1984 data set. F region irregularities have been shown to arise from various instability mechanisms. These processes occur under different conditions of magnetic activity as well as ionospheric parameters. The differing conditions of magnetic activity include strength of magnetic activity, slow versus sudden commencements, length of time of storm etc. The differing conditions of ionospheric and temporal parameters which must be considered include local time of occurrence of the magnetic activity, E region conductivity, and neutral atmosphere parameters in place at the time of the storm.

In this paper we investigated a number of ionospheric parameters observed with the Millstone Hill incoherent scatter radar at the two latitudes where the scintillation observations and the sounder data were taken. We shall attempt to show that at night high convective velocities, primarily E-W, are correlated with irregularity occurrence. In the absence of high velocities i.e. when the electric field is low or when the Harang discontinuity moves thru the path of observations, there is a decrease of irregularity occurrence and intensity. Additionally we shall point out the absence of conditions under which other mechanisms would have been operative. We have examined the magnetograms, the incoherent scatter data and the irregularity observations in detail for several magnetic storms and contrast this with the quiet conditions during one night.

The difficulties involved in uniquely identifying a dominant mechanism for the creation of instabilities is due to many reasons. In the high latitude region the decay of patches of the small scale irregularities is slow. With the existence of a long decay time it is difficult to separate the production of the irregularities from the convection of irregularities into a region. With the possibilities of the small scale irregularities being created by structured precipitation of low energy electrons, gravity waves, and various gradient and temperature related instability processes, it is difficult to single out one mechanism as the sole mechanism for the production of irregularities. The paper being prepared has isolated one of the possible mechanisms for the production of irregularities. The occurrence of high convective velocities was correlated with the occurrence of F-layer irregularities.

As shown by Foster, convection data taken over a relatively long period of time in this longitude region indicate that lower velocities are observed during magnetic storms in

the local midnight time period for latitudes between 60-65°. A minimum in irregularity intensity is also shown in the September 1984 data as well as in the older radio star and satellite scintillation diagrams. Foster has quantified the effect of minimum velocity around local midnight during the Harang discontinuity when the convection is anti-sunward and southward. Bourdillon in 1986 reported observing F-layer irregularities during a period of high velocity westward flow before midnight at geographic latitudes of 54-63° when a substorm started; this was interpreted to be the signature of a sub-auroral ion drift.

There are many mechanisms proposed for creating the F-layer irregularities although ExB and current convective instability mechanisms are those examined in detail by theoreticians in the field. There have been suggestions that diffuse precipitation in the auroral region could destabilize an inhomogeneous plasma having the electron density gradient northward perpendicular to a component of the magnetic field. At auroral latitudes the precipitation would produce a higher electron temperature in the region and the electron density would show decreasing values towards the polar region. On one night, Sep 22-23, we can note a Te increase with scintillation activity and a lowering of Ne. Another mechanism that has been proposed and that has shown evidence of producing irregularities is that of a strong velocity shear. In the midnight time period of Sep 22-23 shears were observed between higher and lower latitudes with high velocities both north and south of Millstone Hill; high level scintillations were recorded. Scintillation activity has also been associated with electron density blobs which have total electron content of several times the ambient ionosphere in the same region.

These mechanisms are certainly operative under various conditions. However within this limited data set of September 17-24, 1984 the most common initiating parameter is a high plasma velocity. In the study we note that the high velocities are primarily E-W although there is no data in this set of observations to indicate that high N-S velocities would not produce the instability conditions necessary for irregularities to develop.

C. SAR ARCS, RED LINE AURORA, AND SCINTILLATION

1. Introduction

Optical observations are being taken by Boston University on a long term basis at Millstone Hill with semi-remote control. Scintillation and ionosonde data are obtainable for the periods when Millstone Hill was running for specific and lengthy campaigns. Several periods are now available when SAR arcs and other events occurred; these data are being reduced.

Through a range of observations, F layer irregularities at auroral and sub-auroral latitudes have been associated with red line auroras and with SAR arcs at plasmopause latitudes. The observations have for the most part been loosely linked i.e. the occurrence of the two F layer phenomena has been associated. It is the purpose of this note to look at the details of the development of the two phenomena in response to the injection and the recovery phase of magnetic storms.

The SAR Arcs have been associated with the ring current. Their observation however has occurred during times when magnetic fluctuations are intense as well as when magnetic activity is relatively quiet. When the magnetic fluctuations were strong during the Oct 20-21, 1981 study, emission at 6300 Å was noted at auroral and sub-auroral latitudes. However during the recovery phase the SAR arcs are frequently separated from auroral optical

emission sometimes by the order of several degrees.

It is the aim of the paper being developed to look at the development of the SAR arcs and 6300 Å aurora and to correlate the optical data with scintillation activity near or through the optical patches.

2. The Periods Studied

Observations from Goose Bay, Labrador and from Hanscom Air Force Base (MA) allowed the plotting of irregularity development particularly for the period April 19-22, 1985 when a magnetic storm developed and when the magnetic field recovered. During the optical events red line intensity extended to 39° N. At the intersection of both FLTSATCOM West and GOES there was red line intensity and a high level of scintillation particularly at 0230 UT.

In the recovery phase of the magnetic storm with SAR arc levels reduced from kilo-rayleighs to 50-100 Rayleighs the intensity of the irregularities was reduced. Observations and analysis were reported in Mendillo et al 1987. These data will be incorporated into the larger study.

A second period under study centered about a magnetic storm with gradual commencement which took place the night of Nov 2-3, 1988. It reached a 5+ level 18-21 UT then gradually decreased.

For the magnetic storm night, the SAR arc hovered over the intersection to the path of GOES. The SAR arc was very strong; the scintillations were saturated at 137 MHz. On this night the last good SAR arc was at 0535 UT but scintillations lasted until 09 UT.

The next night when the magnetic activity had died down a red arc could be noted in the North. Good data was available 0233 and 0728 but no SAR arc was noted at the latitude of the GOES Sagamore Hill intersection. However scintillation was strong 01-09 UT.

It is clear that with the formation of the SAR arc on Nov 3rd there was collocation of the arc and scintillation path irregularities. However on the Nov 4th when Dst was probably high but Kp was low, only irregularities were produced in the region. In summary there are indications of the classical initial phases of the magnetic storm resulting in a SAR arc and irregularities. However during this recovery period conditions were such that only irregularities were produced, in all likelihood by ring current decay.

A third period under study is that of Oct 10-13, 1988. For this period there was a magnetic storm on one night and in addition on next night low levels of magnetic activity with high levels of scintillation activity at sub-auroral latitudes. However Dst data is not available as of the writing of this report. October 12 seems like the recovery period with a good picture of aurora separated from SAR arc.

A series of other good optical observations (clouds and the presence of the moon decrease the number of good SAR arc observations) is to be studied. An initial summary of the various morphology patterns seen in SAR events was presented by Baumgardner, Nottingham, and Mendillo, 1989.

Preliminary correlations indicate that although SAR arcs and F-layer irregularities at sub-auroral latitudes are in general correlated, the detailed correlation can often be absent. There are periods when the intensity of scintillation was very well correlated with red line intensity and other periods which scintillation occurred during nights when SAR arcs occurred

but the detailed correlation was absent. The source (the ring current or auroral effects) may be the same but the mechanism and the necessary and sufficient conditions for production of red line levels and for the generation of F layer irregularities must differ.

D. MAGNETIC STORM DEVELOPMENT AT AURORAL AND SUB-AURORAL LATITUDES

1. Introduction

In order to put the case and statistical studies in useable form, a model is being developed that will describe the F-layer irregularities as they occur during a magnetic storm and with the recovery of the ring current. For the auroral and sub-auroral latitudes, the model that is being validated starts on the day of the magnetic storm. Over a period of several hours in the case of moderate storms the irregularity region spreads equatorwards losing its strength but affecting regions in the U.S. below the Washington, D.C. area for example. If the storm is short lived, on the next day there often is energy in the ring current as shown by the Dst index and there are affects in the sub-auroral and lower auroral regions. A wide range of observations were used. With sounder measurements, in-situ energetic particle satellite observations, scintillations, and SAR arc observations we could look at the time development of irregularities during several magnetic storms. An early version of this study is given in the AGARD paper presented in Munich, Germany and published by AGARD (1989). The data set included observations from Kiruna by L. Kersley of the University College of Wales.

2. Origins of sub-auroral irregularities during the growth phase of a storm

During periods of increased geomagnetic activity the electric field at mid-latitudes can be enhanced by a number of mechanisms. As the level of disturbance increases, the two-cell ionospheric convection pattern driven by the magnetospheric electric field expands to low latitudes, resulting in enhanced sunward convection at previously sub auroral latitudes.

During the injection phase of the magnetic storm, the auroral effects including F-layer irregularity intensity expand to lower latitudes. Insofar as the occurrence and intensity of F-layer irregularities are concerned they often extend to 50° corrected geomagnetic latitude. The onset and early levels of F-layer irregularities at latitudes below the auroral region during this phase of the magnetic storm may be due to either the direct action of an electric field, energetic particle precipitation or the formation of irregularities at higher latitudes and their subsequent transport to lower latitudes. During the magnetic storm, the electric fields and high convection velocities probably play a role in producing the conditions for instabilities from auroral to sub-auroral latitudes. This would account for the irregularity activity on the first day of the magnetic storm.

3. Dst and the recovery period

The storage aspects of the ring current's long recovery allow for effects on the irregularities in the F layer at sub-auroral latitudes. The storage effects, which take place in the second and at times on the third day after the initial injection phase of the magnetic storm, are observed during relatively quiet periods of magnetic activity.

With the understanding of the development of irregularities during magnetic storms, it will be necessary to identify precisely the plasma instability responsible for the formation of the irregularities and the way in which energy is transferred from the ring current into the plasma at F region altitudes.

E. AURORAL TO EQUATORIAL F-LAYER IRREGULARITIES DURING MAGNETIC STORMS

In October 1988, Dr. N. Balan joined us from India for a 3 month period. His task was to organize data on a series of magnetic storms during the solar maximum flux period of Sep 15-Nov 15, 1981. The data set had been reduced by J. Aarons. A paper showing the coupling of equatorial and auroral effects had already been published in the Proceedings of the Ionospheric Effects Symposium but the paper had not been submitted as a journal paper. The concept was to expand the data base.

The effects of magnetic storm phases on F layer irregularities from auroral to equatorial latitudes in a nearly constant western longitude zone were outlined by considering scintillation, spread F, and low energy electron precipitation data for five magnetic storms that occurred during the high solar flux period September November 1981. The effects which are different in the equatorial and high latitude regions are found to depend not only on the phases of the storms but also on their intensity and duration.

In the equatorial region, F layer irregularities are generally inhibited during the injection phase and early part of the recovery phase irrespective of the time of start of recovery. Irregularities are found to reappear during the recovery phase when Dst falls below about -75nT and continue up to sunrise on the first night and well beyond postmidnight on the second night after reappearance. Even during the recovery phase, irregularities are found to be suppressed if there is a negative slope in the Dst variation. In one case of a moderate storm with many fluctuations in Dst in the injection phase, strong irregularities are observed from evening to well beyond sunrise during this time.

In the high latitude region, F-layer irregularities are found to be generated at the auroral latitude during the injection phase, the strength and duration of which vary with the intensity and duration of the magnetic activity. With the development of the magnetic storm the conditions which produce F-layer irregularities descend to what had been subauroral latitudes. During the recovery phase with low magnetic activity and low intensity auroral irregularities, we found low-energy electron precipitation occurring across subauroral regions according to DE-2 data. Relatively strong F layer irregularities were found in the subauroral regions. During the recovery phase F-layer irregularities at very low levels are observed even down to 30° magnetic latitude.

Much research has been done on the effect of magnetic activity on F layer irregularities at auroral and at equatorial latitudes. At high latitudes a review of the data indicates a rather complex picture with a seasonal, latitudinal and longitudinal dependence. In most of the studies, the data are analyzed by sorting into magnetically disturbed and quiet days depending on whether the sum of Kp or Ap is greater than or less than a particular value. However the effects of magnetic storms on F region irregularities undoubtedly depend on the phases of the storms. For a particular observing point this means a correlation of the effects of storm development as a function of local time. This has been shown to be amply

true in the case of total electron content obtained from satellite observations. In the case of equatorial F layer irregularities several studies have shown correlation with the phase of the storm. These studies were limited to the use of data from either equatorial or high latitude regions; in the ongoing study we have attempted to study the effects of magnetic storm phases on a global scale. The data base included those observations from stations listed in Table 1 and others at equatorial latitudes along a nearly constant western longitude zone. The data are recordings taken during five magnetic storms that occurred during the high solar activity period of September-November 1981. Results from an earlier analysis of three additional magnetic storms in this period of high solar flux have been reexamined and are incorporated into the conclusions. Low-energy electron precipitation recorded by the DE2 satellite, magnetograms, and Dst and Kp indices are also used for the study.

The results that emerge from these observations indicate that the effects of magnetic storm phases on F region irregularities in the equatorial and high latitude regions depend not only on the phases of the storms but also on their intensity and duration.

Out of the five storms studied, in three cases having long duration main phases, scintillations in the equatorial regions are found to be inhibited during the main phases and early part of the recovery phases. Dst values during the main phases when scintillations were inhibited are below -50nT in all three cases. In one case of an intense storm having a short duration main phase, equatorial scintillations present during the initial positive phase are suppressed from a high level of 30 dB to a low level of 2 dB during the injection phase when Dst falls below about -50nT . In a moderately severe storm with Dst showing strong fluctuations in level in the main phase, high level scintillations were observed during the evening to well beyond sunrise at the equator.

Time of start of the recovery phase was found to have no effect on the equatorial F region irregularities. Irregularities are found to reappear during the recovery phase of the storms when Dst rises above about -75nT . Once the irregularities reappear, they are strong and are found to continue up to sunrise on the first night and beyond postmidnight on the second night. However, intense irregularities causing scintillations in L band are not generally observed beyond midnight in the equatorial anomaly region. Even after reappearance, the irregularities are found to be suppressed again (in three cases) when there were negative slopes in the Dst variations. There are indications to show that inhibition of equatorial irregularities occur have a localized component which affect their generation.

In the high latitude regions, strong scintillations are observed at the auroral intersection during the main phase of all the five storms, strength and duration of the activity varying with the intensity and duration of the phase. Irregularities (scintillations and spread F excursions) observed in the subauroral regions during the injection phase are weak compared to those at the auroral latitude and are observed generally after midnight. During the recovery phase, when irregularities at the auroral latitude become weak both in strength and duration, in general, irregularities in the subauroral latitudes are found to be stronger than those observed during the main phase. There are two cases with strong irregularities in the subauroral latitudes and low level irregularities in the auroral latitudes during the recovery phase. Weak scintillations were also observed around 30° magnetic latitude during postmidnight hours during the recovery phase of three of the storms for which data are available.

Magnetograms taken by the AFGL magnetometer networks show activity during the

main phase and little activity during the recovery phase of all the storms. Latitudinal extent of low energy (less than 12 eV) electron precipitation, in general, is above the subauroral intersection during the main phase, below the auroral intersection and crosses the subauroral intersection during the recovery phase. Irregularities observed in the subauroral latitudes during the main phase are produced by the development of the magnetic storm with either conditions necessary for the generation of the irregularities descending to lower latitudes or the irregularities convected into the region; the data base for this paper cannot be used to comment on the validity of either mechanism.

IV. CONCLUSION AND FUTURE STUDIES

Our principal program was to study the dynamics of F layer irregularity development and decay. It is at F layer heights that communications over long distance is achieved and it is at F layer heights that irregularities produce serious effects of trans-ionospheric and reflected HF transmissions.

We are concluding certain studies and starting on new programs. The period September 1981 is still being subjected to intensive data analysis. Incoherent scatter measurements of electron density, electron temperature, and convection velocities are being compared to scintillation observations, ionospheric sounding and in-situ observations. This is being worked with J. Foster of Millstone Hill and A.S. Rodger of the British Antarctic Survey; the emphasis is on validation of various instability mechanisms.

From the present study at auroral and sub-auroral latitudes we believe we have shown that at night high convective velocities, primarily E-W, are correlated with irregularity occurrence. In the absence of high velocities i.e. when the electric field is low or when the Harang discontinuity moves thru the path of observations, there is a decrease of irregularity occurrence and intensity. We expect to complete this work in a paper now in an early draft form.

One collaborative study of F-layer irregularities with data from 70° West, the UK and Northern Europe undertaken by J. Aarons with A.S. Rodger of the British Antarctic Society and L. Kersley of the University College of Wales has been completed. The concept was to plot irregularity intensity during quiet magnetic periods and during magnetic storms over a range of latitudes. The results were presented at an AGARD Symposium on Ionospheric Structure and Variability on a Global Scale in May, 1988 and published in the May 1989 AGARDOGRAPH. However the study is being broadened to develop a model of the development of irregularities as a function of the phases of magnetic storm development.

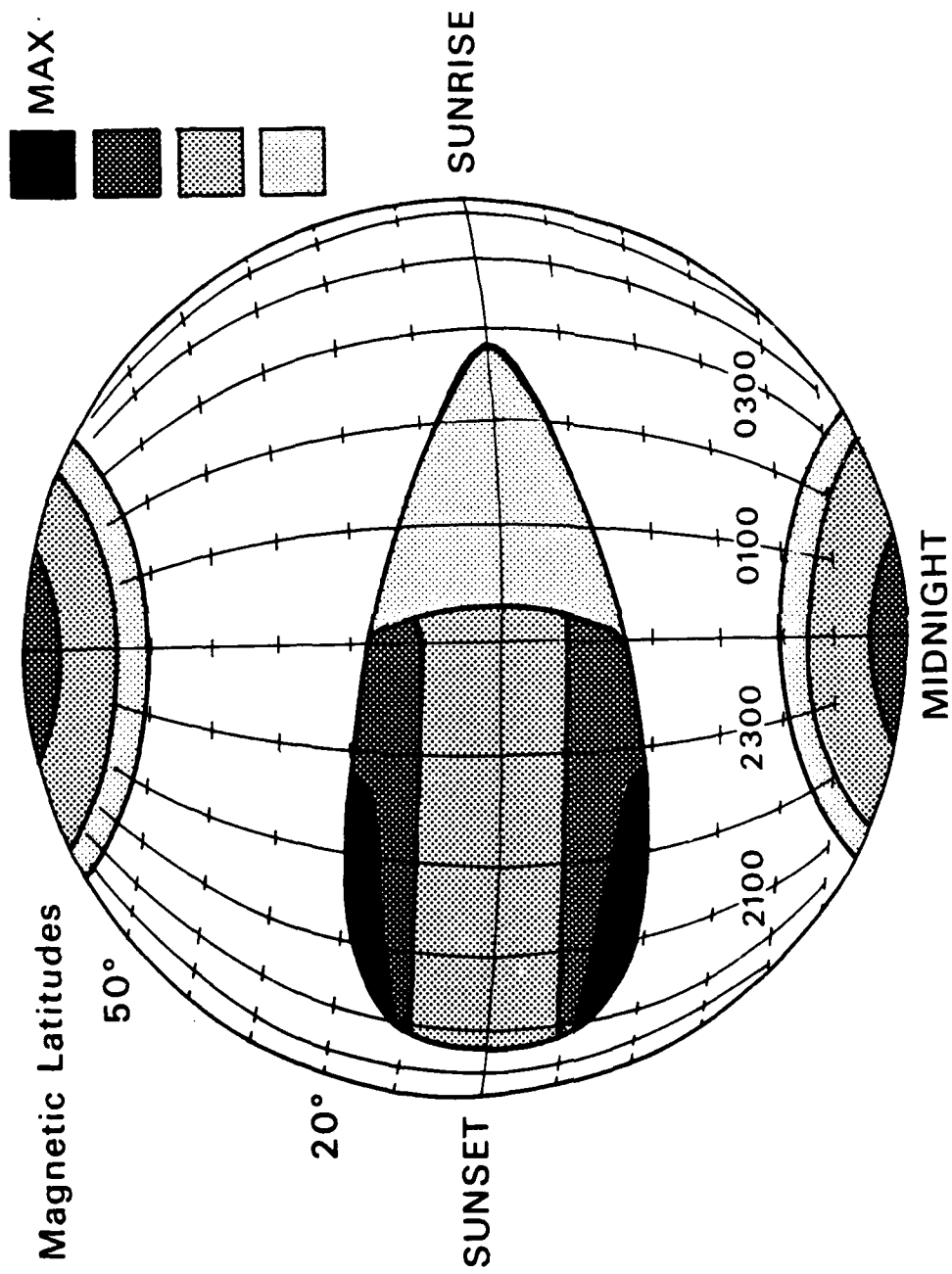
In the equatorial region the principal question in F layer dynamics that is unresolved is the source or trigger of quiet period plumes that produce deep fading on radio signals. Rocket experiments (Condor) failed to reveal any new information on the triggering mechanism for the plume. No study was offered to reveal the cause of the day to day variations of the equatorial F layer irregularities. While there are papers which purport to link the origin of the patch with E layer and tropospheric parameters no one-to-one experiment has even attempted to determine the necessary conditions for the origin of patches of irregularities.

A new way of looking at the origin of equatorial bubbles will be investigated. During certain seasons at a particular longitudes on the magnetic equator, bubbles are observed on almost any night. The new concept is to assume that the conditions for nightly development of irregularities are present and an event occurs that spoils the normal development. Thus

we are looking for spoilers rather than triggers. In the longitude region from 15° to 70° West for example in October and March we expect bubbles every night. Something spoils this. However at the same longitude, bubbles or patches are the exception and rarely occur in July and August. We know that electric field changes produced by the ring current lift the F layer electron density peak; subsequently when it falls bubbles are created. This then is a trigger and bubbles are observed. The outcome of this new approach is to look for spoilers during seasons of great activity and triggers during periods of low activity.

Topics which remain to be addressed in equatorial aeronomy in future years include the physics of coupling between the solar wind and the equatorial ionosphere. A set of coordinated observations was taken in the Kwajalein and Wake Island region in August 1988. This series of radar, optical, and radio measurements plus some satellite recordings will be studied primarily to determine if unique circumstances produce triggering of equatorial bubbles during certain seasons and prevent the development of bubbles during other seasons.

Perhaps the most interesting area will be to study the linking of magnetospheric and auroral parameters with equatorial effects. A study of the physics involved will have to reveal the linkage mechanism probably via the ring current. In one illustration of the linkage of equatorial and high latitude effects, we observed intense scintillation levels at Goose Bay, Sagamore Hill, and the Argentine Islands during a magnetic storm and a cut off of scintillation activity at Huancayo, Peru and Ascension Island, the equatorial stations. When the storm subsided on the next day there was still activity at the higher latitudes and irregularities returned to the equatorial region.



FADING DEPTH DURING HIGH SUNSPOT YEARS

V. PUBLICATION AND PRESENTATION SUMMARY OF BOSTON UNIVERSITY PERSONNEL SUPPORTED BY CONTRACT

PUBLICATION

- Aarons, J., C. Gurgiolo, and A. S. Rodger, The effects of magnetic storm phases on F-layer irregularities below the auroral oval: *Radio Science* 23, 209, 1988.
- Aarons, J., C. Gurgiolo, and A.S. Rodger, The effects of magnetic storm phases on F layer irregularities from auroral to equatorial latitudes. Publication in the Proceedings of the Ionospheric Effects Symposium Library of Congress Catalog Card 87-619868, 1988.
- Aarons, J. and A.S. Rodger, Sub-auroral F-layer irregularities and the ring current, *Ann. Geophysicae* 7, (2), 169-176, 1989.
- Aarons J., Foster, J. C., Kersley, L., Rodger, A.S., Auroral and sub-auroral F-layer irregularity studies in the northern and southern hemisphere during the Equinox Transition Study September 16-26, 1984, AGARDOGRAPH Conference Proceedings No. 441, April 1989.
- Foster, J.C., and J. Aarons, Enhanced anti-sunward convection and F-region scintillations at mid-latitudes during storm onset *J. Geophys. Res.* 93, 11,537-11,542, 1988.
- Mendillo, M. J. Baumgardner, J. Aarons, J. Foster, and J. Klobuchar, Coordinated optical and radio studies of ionospheric disturbances: Initial results from Millstone Hill, *Annales Geophysicae* 5A, (6), 543-550, 1987.
- Mendillo, M.J., J. Baumgardner, J. Providakes, Ground based imaging of detached arcs, ripples in the diffuse aurora and patches of 6300 Å emission, *J. Geophys. Res.* 94, 5367-5381, 1989.
- Rodger, A.S. and J. Aarons, Studies of ionospheric F-region irregularities from geomagnetic mid-latitude conjugate regions, *J. Atmos. and Terr. Phys.* 50, 63, 1988.

The following paper has been accepted for publication in 1989:

- Goodman, J. and J. Aarons, Ionospheric effects on modern electronic systems. Invited review paper to be published in *Proceedings of IEEE*, 1989.

Invited and Contributed Presentations at Topical or Scientific/Technical Conferences

- Aarons, J. and A.S. Rodger, Magnetic storm effects on F layer irregularities near the auroral oval. Poster and review presentation at URSI General Assembly August 1987.
- Aarons, J., Foster, J. C., Kersley, L., Rodger, A.S., Auroral and sub-auroral F-layer irregularity studies in the northern and southern hemisphere during the Equinox Transition Study September 16-26, 1984 Presentation at the AGARD Symposium on Ionospheric Structure in Munich, Germany May 1988
- Aarons, J., Presentation at Workshop on Equinox Transition Study "Scintillation activity from sub-auroral and auroral latitudes" Hanscom AFB, MA, January 1988.
- Aarons, J., Foster, J.C. and A.S. Rodger, F-layer irregularities and incoherent scatter parameters during the September 1984 Equinox Transition Study American Geophysical Union Fall Meeting December 1988.

- Baumgardner, J. D., Nottingham, and M. Mendillo, Red arcs we have seen: CEDAR Imaging at Millstone Hill *EOS*, **70**, 105, 1989.
- Foster, J.C. and J. Aarons, Enhanced anti-sunward convection and F-region scintillations at Mid Latitudes during substorm recovery presented at the Equinox Transition Study Workshop, January 1988.
- Rodger, A.S., J. Aarons, and J.S. Foster, F-Region ionospheric F-region irregularities at geomagnetic mid-latitudes Paper presented at IAGA Exeter, July 1989.

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